

# Explore the Lifetime Frontier with MATHUSLA

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15<sup>th</sup> Topical Seminar on  
Innovative Particle and Radiation Detector

**W**  
UNIVERSITY of  
WASHINGTON

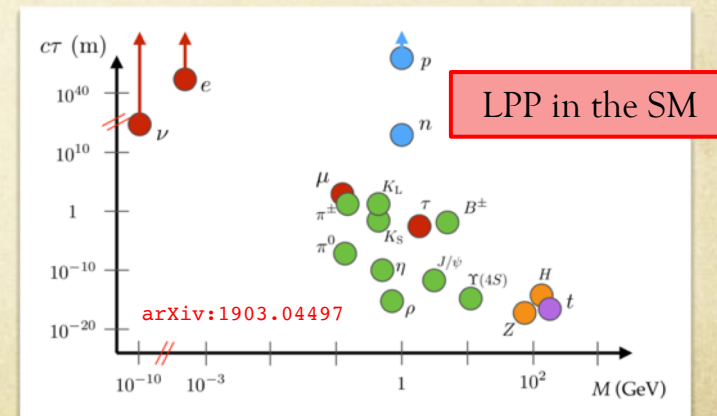
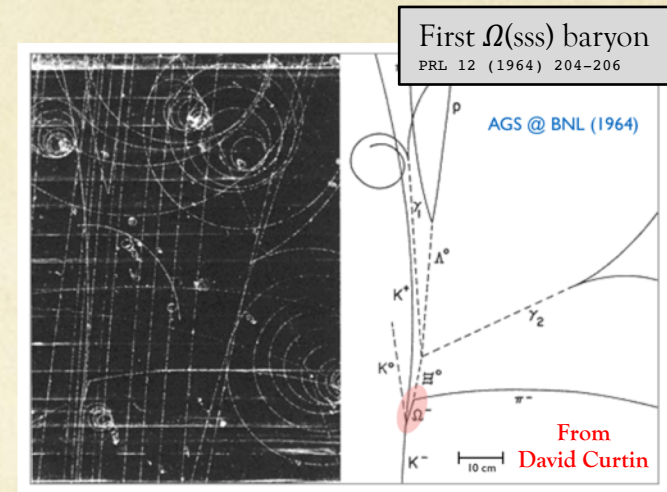
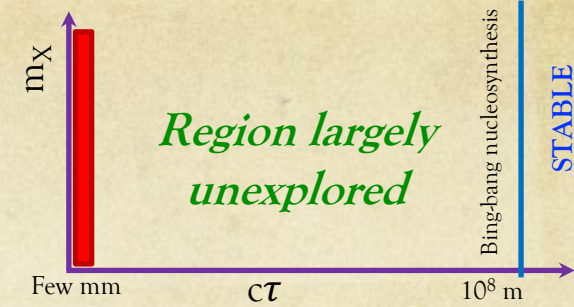
14<sup>th</sup> October 2019

Siena

**MATHUSLA**

# Unconventional Searches @ LHC

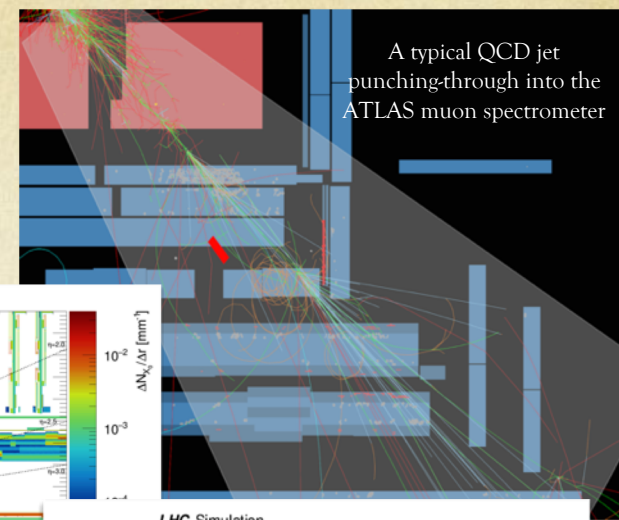
- Current searches at 13 TeV show an **impressive agreement** with the **SM expectations**
- New physics should be present at
  - ✓ High mass → no hints so far
  - ✓ **Small coupling** → **not fully explored**
- Many extensions of the SM include particles that
  - ✓ Are **neutral**, **weakly coupled**, and **long-lived** that can decay to different final states (hadrons, leptons, photons, etc)
    - Several mechanism behind long-lived particles (LLPs): approximate symmetry, heavy mediators, etc...
  - ✓ Are **charged** meta-stable/stable
    - Multi-charged particles predicted by Technibaryons, almost-commutative leptons, doubly charged Higgs



Need to **exploit the full LHC potential** and **reduce to negligible the possibility of losing new physics at the LHC!**



# Unconventional Challenges

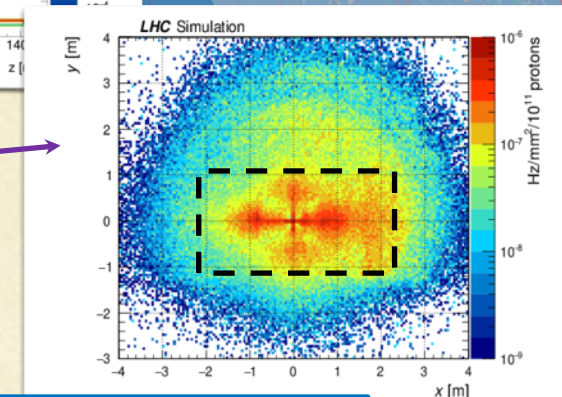
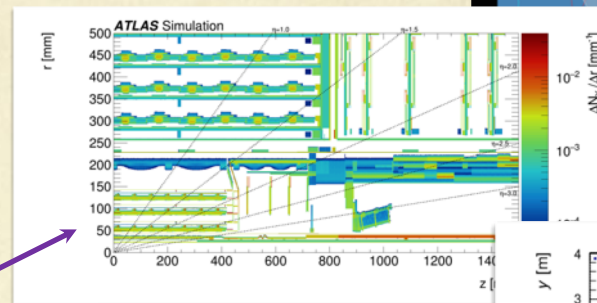


A typical QCD jet punching-through into the ATLAS muon spectrometer

- BSM particles can produce **final states** that might be **very difficult to study** due to

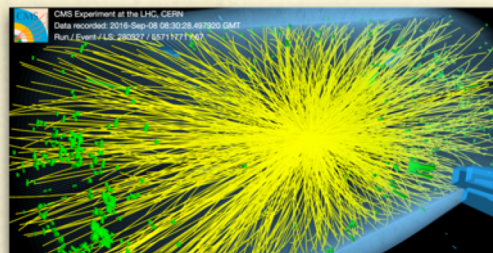
- ✓ **Complicated backgrounds**

- Instrumental backgrounds
- Large QCD jet production
- Pile-up problems
- Material interaction
- Beam induced background (BIB)
- Cosmic background

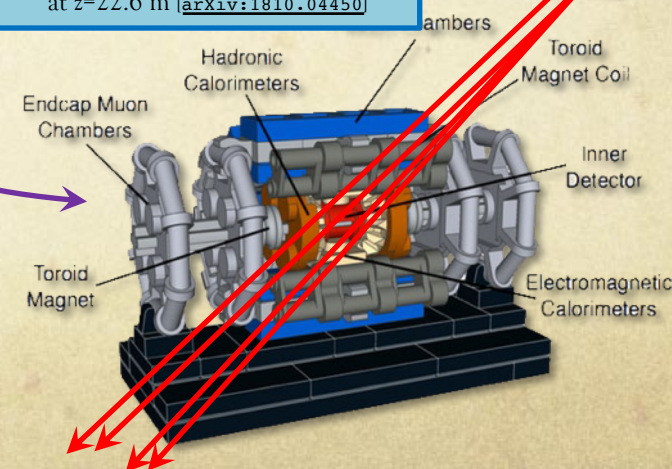


muons ( $E > 20$  GeV) entering ATLAS  
at  $z = 22.6$  m ([arXiv:1810.04450](https://arxiv.org/abs/1810.04450))

- ✓ **Constraints in triggering**



- At HL-LHC → best possible sensitivity from ATLAS displaced vertex search in the muon spectrometer (**shielded and able to trigger on LLP at L1**), but searches ([arXiv:1605.02742](https://arxiv.org/abs/1605.02742)) suggest that various backgrounds (punch through, cosmes, etc) of the order 100 fb



# MATHUSLA

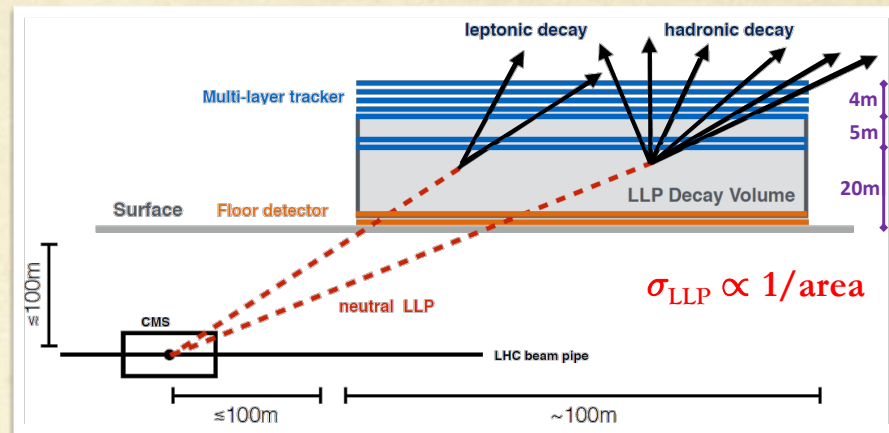
*(MAssive Timing Hodoscope for Ultra Stable neutraL pArticles)*



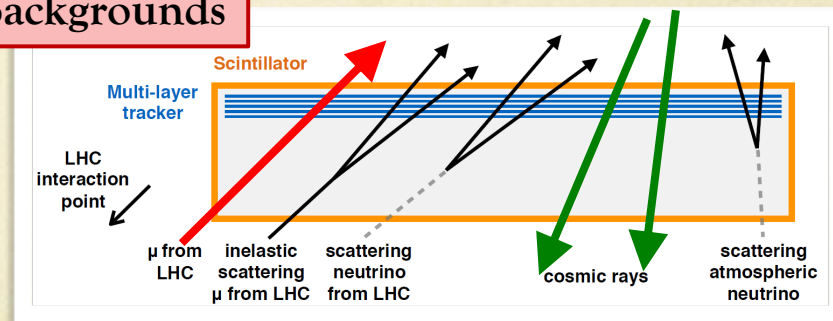
# MATHUSLA - Layout

- arXiv 1606.06298
- arXiv 1806.07396
- CERN-LHCC-2018-025

- Dedicated detector **sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis** (BBN) limit ( $10^7 - 10^8$  s) for the HL-LHC
- Proposed a **large area surface detector located above CMS**
  - ✓ Need **robust tracking**
  - ✓ Need **excellent background rejection**
  - ✓ Need a floor detectors to reject interactions occurring near the surface
  - ✓ Both **RPCs** and **extruded scintillators coupled to SiPMs** are considered (good time/space resolution)
- ❖ **Cosmic muon** rate of about 1.7 MHz ( $100\text{m}^2$ ) and 10 Hz **LHC muon** rejected with timing
- ❖ **LHC neutrinos**: expected 0.1 events from high-E neutrinos (W, Z, top, b), ~1 events from low-E neutrinos ( $\pi/K$ ) over the entire HL-LHC run
- ❖ **Upward atmospheric neutrinos** that interact in the decay volume (70 events per year above 300 MeV) “decaying” to low momentum proton

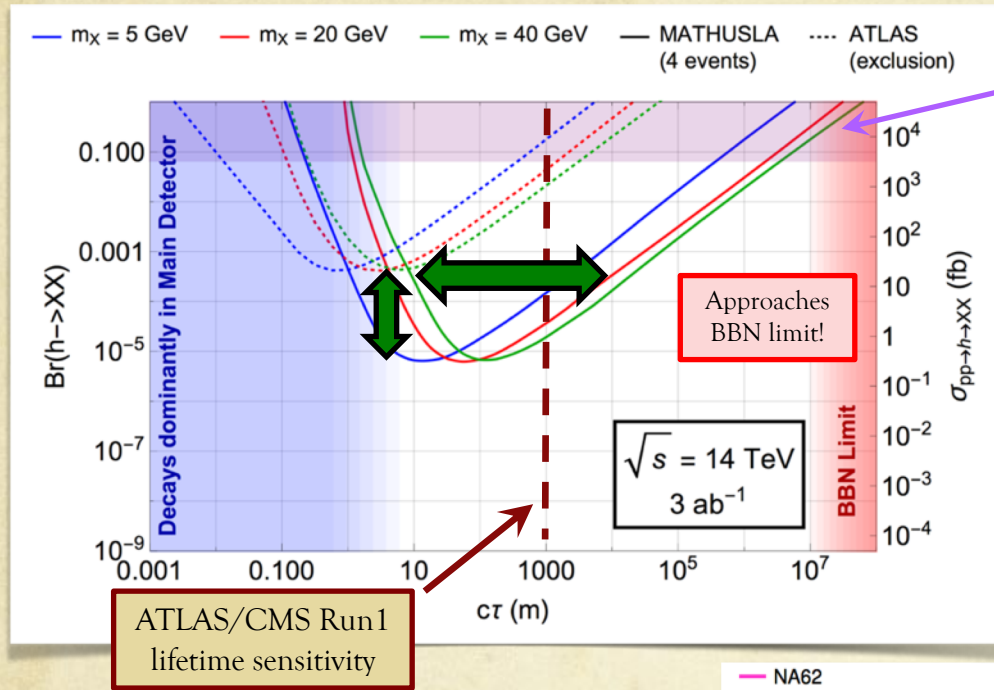


## Backgrounds

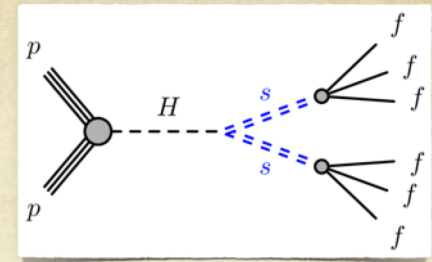


# MATHUSLA - Physics Reach

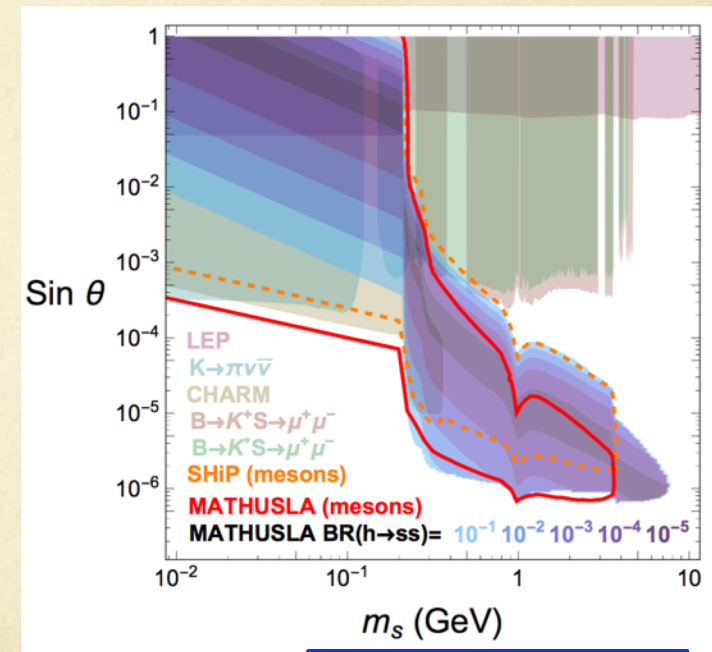
arXiv:1806.07396 [hep-ph]



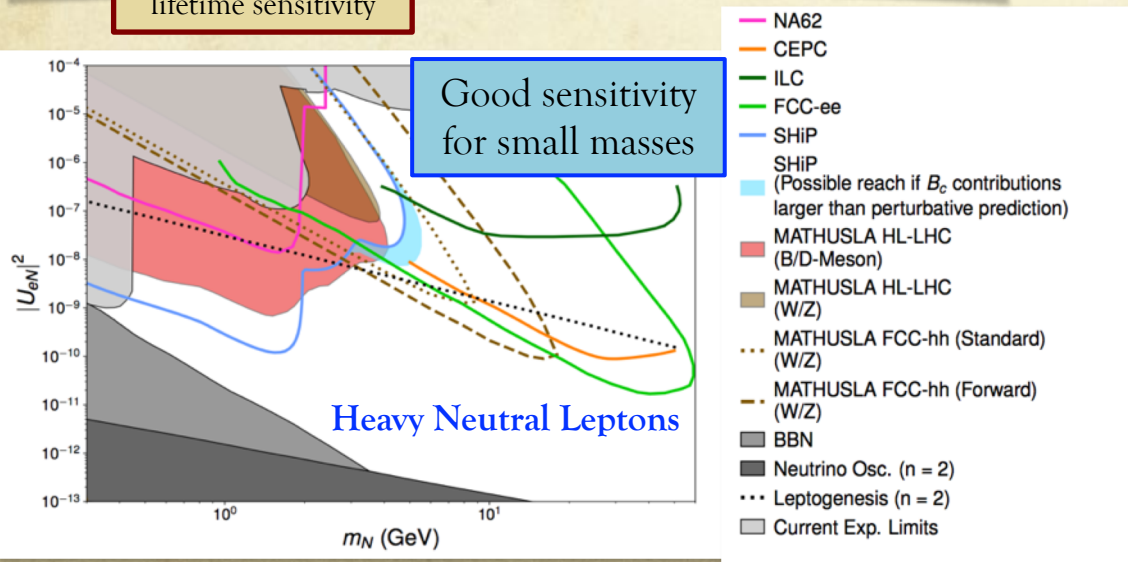
h  $\rightarrow$  inv  
HL-LH limit



- Can probe LLPs at GeV to TeV
- Good sensitivity for mass scale above  $\sim 5$  GeV, and for lifetime  $\gg 100$  m even at low masses



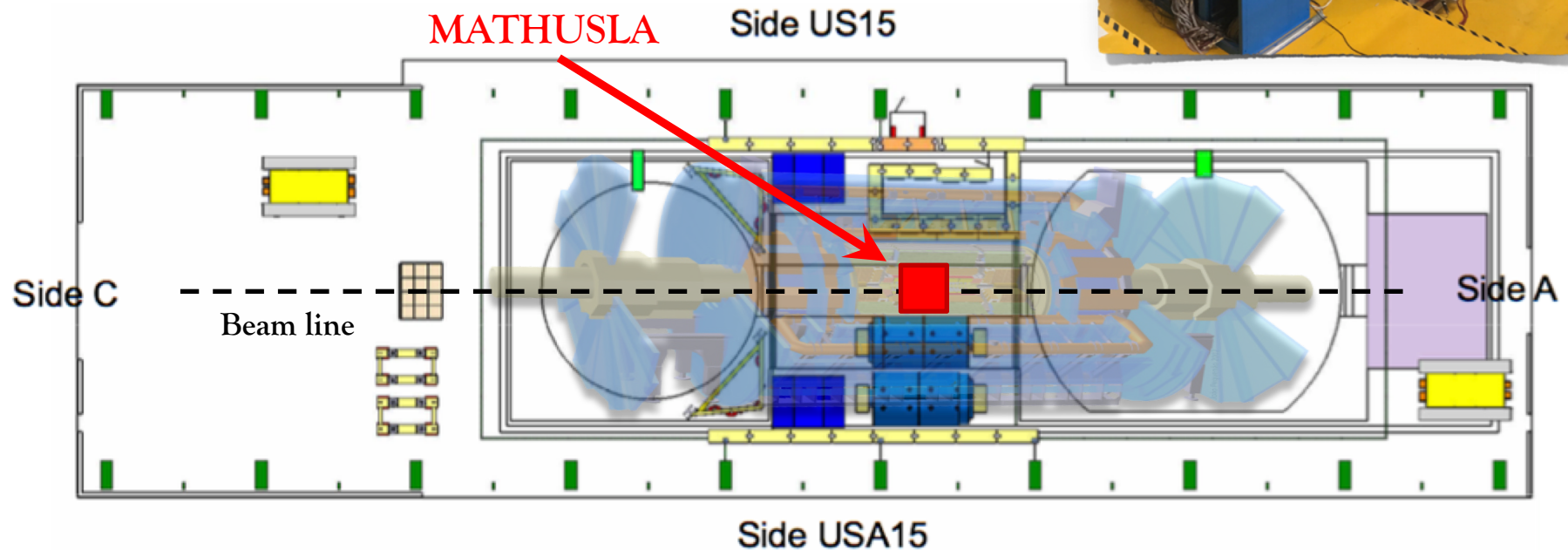
Higher sensitivity for  
long lifetimes





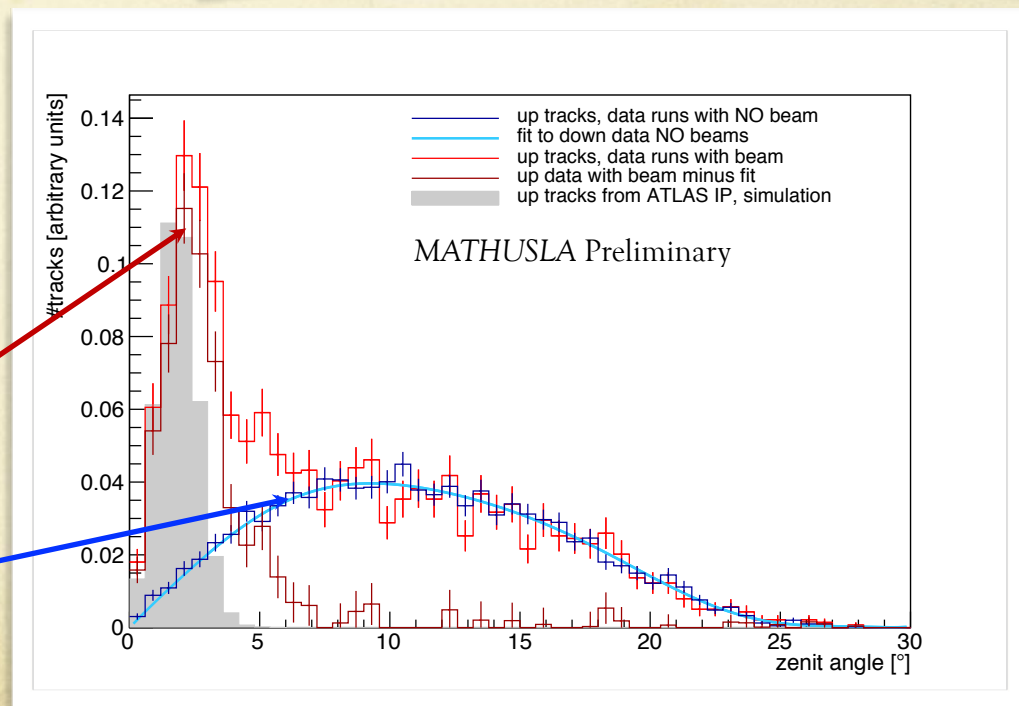
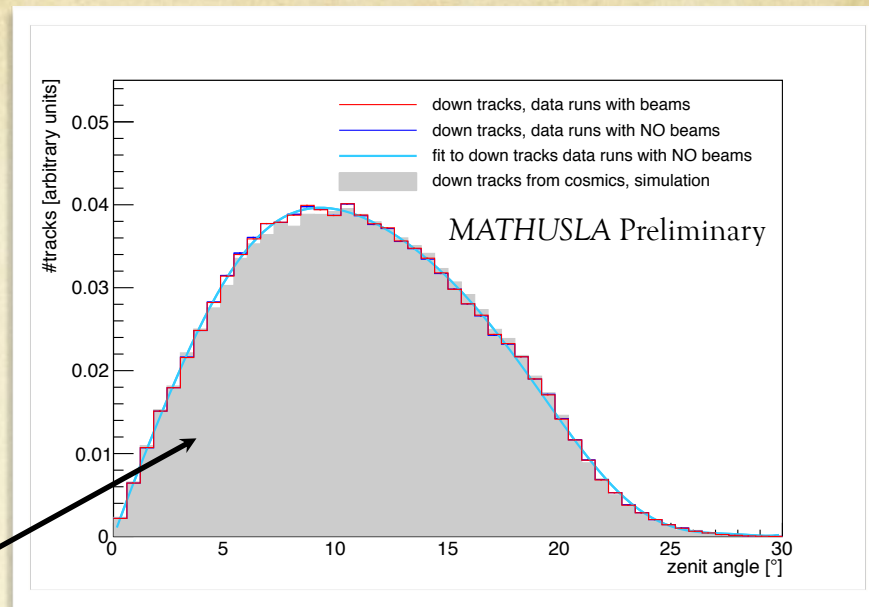
# Test Stand @ P1

- Cosmic background ( $\sim$ ) well understood
- Need to quantify the **background from ATLAS**
- Test stand installed in the (Buffer Zone) on the surface area above ATLAS (exactly above IP) in November 2017 (during ATLAS operations this space is empty)
  - ✓ Perform measurements with beam on and off during 2018



# Test Stand Data Analysis

- Took data in different LHC conditions (w/wo beam)
- MC simulation for cosmic muons and for particles generated at the ATLAS IP
- Preliminary results – MC not corrected for efficiency or multiple scattering
  - Angular distribution for down tracks (cosmic muons) match very well expected from MC
  - Arbitrary normalization
- ❖ Accumulation for zenith angle  $< \sim 4^\circ$  consistent with upward going tracks from IP when collisions occur
- ❖ Up tracks no beam consistent with downwards tracks faking upwards tracks



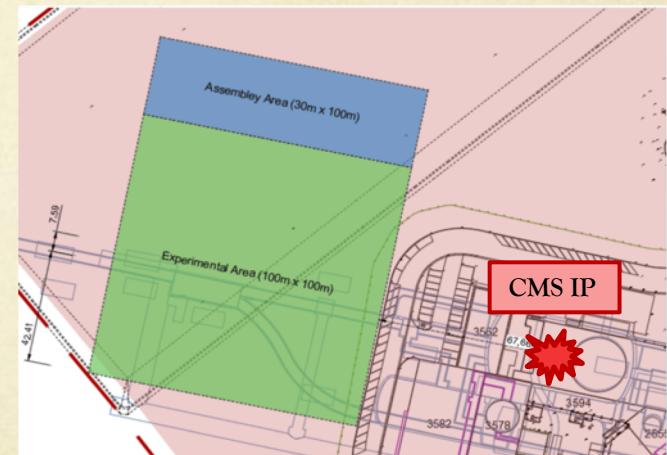
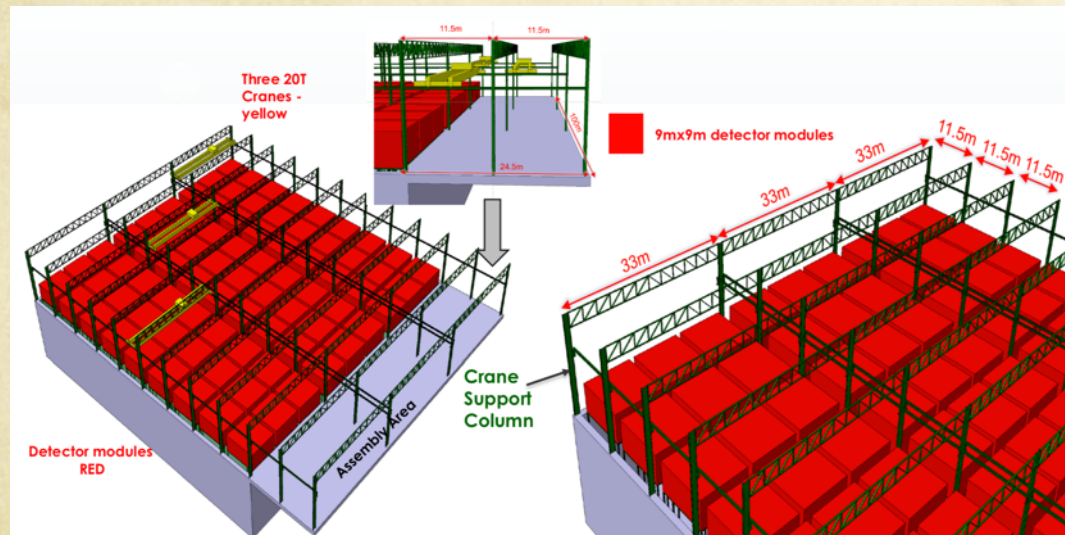
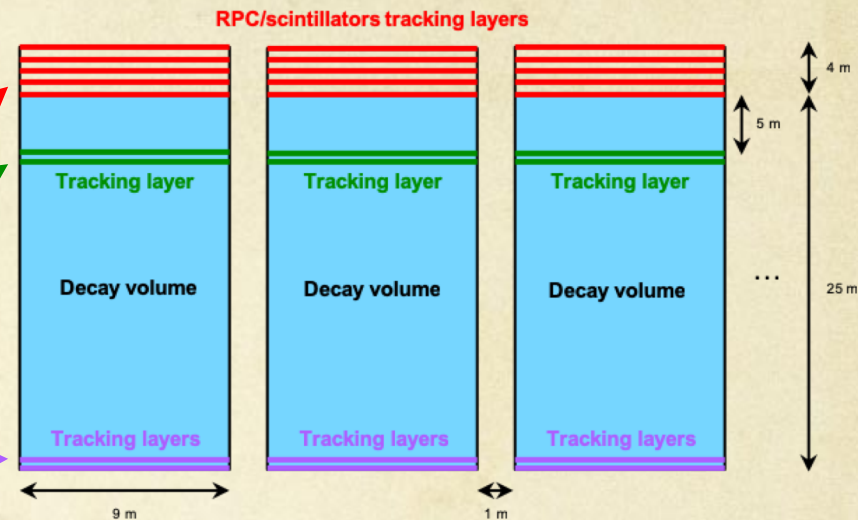


# MATHUSLA @ P5

Finalised soon!

- Working with Civil Engineers to define the building and the layout of MATHUSLA at P5
- Layout restricted by existing structures based on current concept and engineering requirements

- Assume ~ **25 meter decay volume**
- Individual detector units  $9 \times 9 \times 30 \text{ m}^3$
- **5 layers of tracking/timing detectors** separated by 1m
- Additional **tracking layer 5m**
- **Double layer floor detector**



- ❖ 68 m to IP on surface and IP ~80m below surface
- ❖ ~7.5m offset to centre of beam

❖ **Gain of 1.5 wrt detector at 100 m and IP 100 m below!**

# What's the best tracking technology?

## RPCs used in many LHC detectors

### ✓ Pros 😊

- Proven technology with good timing and spatial resolution
- Costs per area covered are low

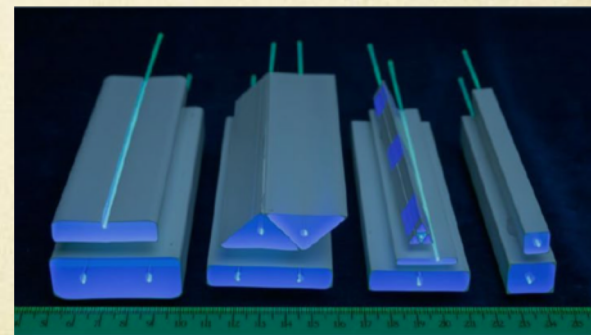
### ✓ Cons ☹️

- Require HV  $\sim 10$  KV
- Gas mixture used for ATLAS and CMS has high Global Warming Potential (GWP) and will not be allowed for HL-LHC (attempting to find a replacement gas)
- Very sensitive to temperature and atmospheric pressure

Extruded **scintillator** bars with wavelength shifting fibers coupled to SiPMs makes this technology cost wise competitive with RPCs

### ✓ Pros 😊

- SiPMs operate at **low-voltage** (25 to 30 V)
- **No gas** involved
- **Timing resolution can be competitive with RPCs**
- Tested extrusion facilities - **FNAL** and Russia. Used in several experiments: Bell muon system trigger upgrade (scintillators from FNAL and Russia), Mu2E, and KIT (FNAL scintillators)





# Extruded scintillators @ Fermilab

## ➤ Extruded scintillator facility at Fermilab

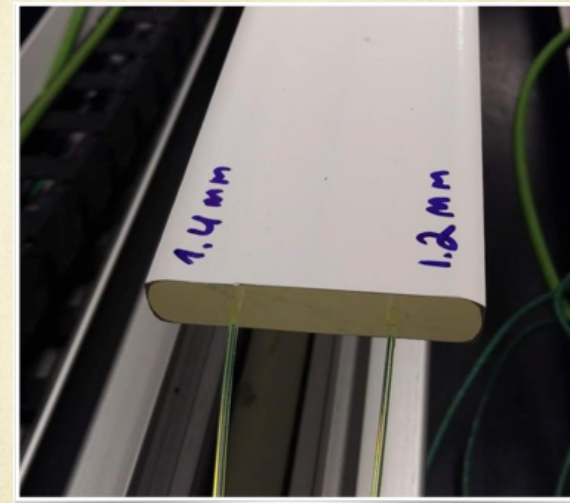
- **100 ton per year** using 6 hour shifts 4 days per week (2 shifts → 200 t/y)
- Typical production 50t/y, demand driven
- Used for many experiments, most recently **Mu2e, KIT**
- Cost \$20/kg in small-ish quantity (1/2 labor, 1/2 chemicals)
- Target of \$10/kg in large quantity

## ➤ Already tested

- 3.2 m Mu2e extrusion (co-extruded with white polyethylene reflector)
- Scintillator extrusion has lots of light (**>70 pe/MIP worst case in middle**)
- **Spatial resolution 15 cm with simple algorithm, can likely do better**

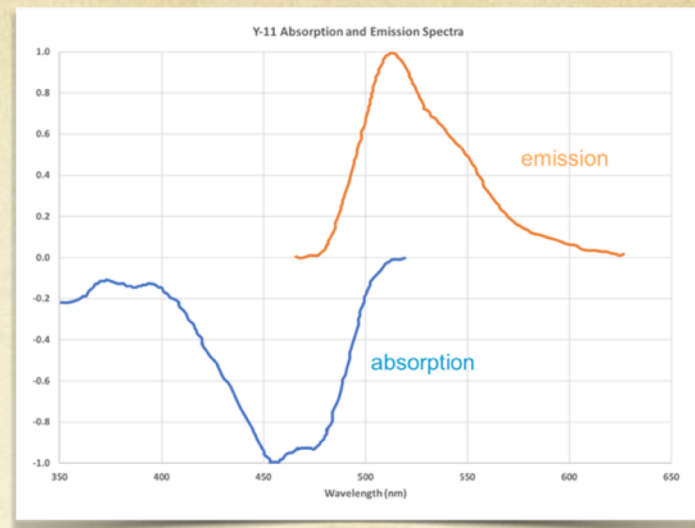
## ➤ Tests done with 1 cm thick bars

- Try 0.5 cm ?
- Two fibers present in extrusion, second fiber eating some (half?) of the light



# WLS fibre & SiPM

- For **WLS** considering **Kuraray Y-11** (< \$5/m)
  - Cutoff below ~500 nm by self-absorption
  - Peak at ~520nm (**green**)
- SiPM used in HEP
  - Detection efficiency typically peaks around **450 nm**
  - Drops off for longer wavelengths
  - Reasonably matched to scintillation light (blue) but not as well for WLS
  - Best(?) that can be done with off-the-shelf items
- Possible **improvements in SiPM spectral response?**
  - Green light penetrates deeper in silicon than blue light
  - Sometimes electrons liberated beyond collection layer
  - Manufacturing process can be tweaked to increase thickness of the collection layer
  - Improvement over standard processing by a factor of 1.5 seems possible (for wavelengths away from peak efficiency)
  - Engineering R&D effort guesstimated to be 3 person-months



## Possible options:

- S14160-3050HS: 3x3mm
- S14160-6050HS: 6x6mm



# Readout & Data Taking

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## ➤ Readout

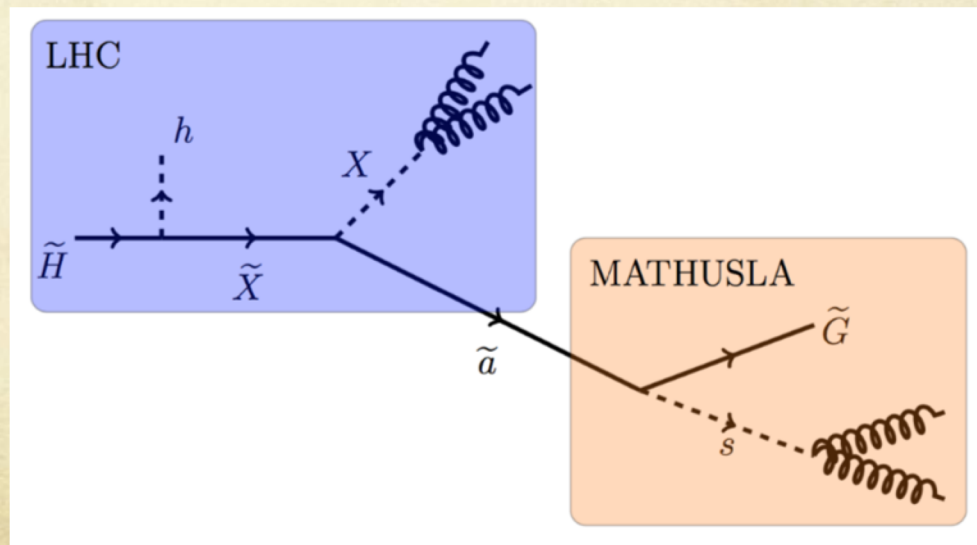
- 8 tracking layers (5 tracking layers + 5m below + 2 on the floor)
- 4 cm scintillators with readout in both ends results in 800K channels
- Rates dominated by cosmic ray rate ( $\sim 2$  MHz)
  - ✓ Does not require sophisticated ASIC
  - ✓ Aiming for 1 CHF per channel for frontend

## ➤ Data taking

- Baseline is to collect all detector hits with no trigger selection and separately record trigger information
- Data rate dominated by cosmic rays  $1/(\text{cm}^2\text{-minute})$  which gives  $\sim 2$  MHz rate. With  $9 \times 9$  m<sup>2</sup> modules, two hits/module with 4 bites per readout and readout 7 layers to readout gives  $\sim 30$  TB /y per module
- Move information to central trigger processor
- Trigger separately recorded (and used for connecting to CMS detector bunch crossing in the future main detector)

# Trigger

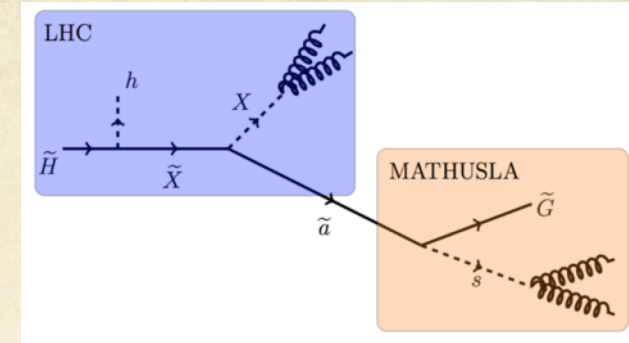
- CMS Level-1 trigger latency is  $12.5 \mu\text{s}$  for HL-LHC
  - ✓ Conservatively assuming a 200m detector with height = 25m located 100m from IP, LLP with  $\beta = 0.7$ , optical fiber transmission to CMS with  $v_{\text{fiber}} = 5 \mu\text{s}/100\text{m}$
  - ✓ MATHUSLA has  $9 \mu\text{s}$  or more to form trigger and get information to CMS Level-1 trigger
  - ✓ If problem to associate MATHUSLA trigger to unique bunch crossing (b.c.) the approved CMS HL-LHC Level-1 allows for recording multiple b.c's
- Running CMS and MATHUSLA in “combined” mode will be crucial for both cosmic ray studies and LLP searches





# MATHUSLA – Major Challenges and Strengths

- Access to much longer lifetimes up to BBN and very high masses
- HL-LHC CMS trigger latency  $12 \mu\text{s}$
- Large detector  $\rightarrow$  constraints on instrumentation options
- Need a building and associated infrastructure
- Cosmic ray physics (guaranteed return on the investments)

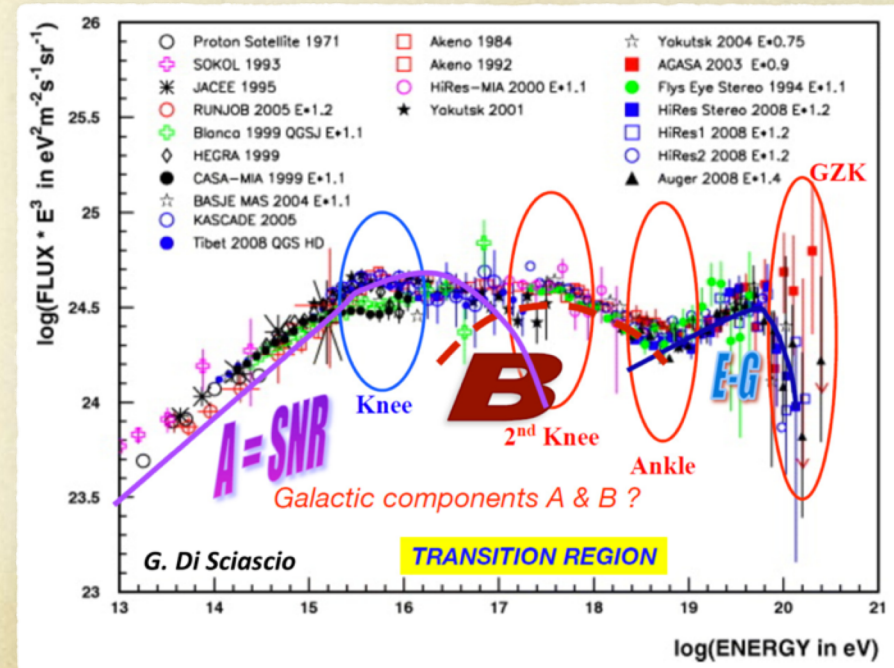


## ✓ MATHUSLA standalone

- Reconstruction of the core, direction of the shower, slope of the radii distribution of particle densities, total number of charged particles

## ✓ MATHUSLA+CMS

- Uniquely able to analyse muon bundles going through both detectors. Powerful probe of heavy primary cosmic ray spectra and astrophysical acceleration



# Summary & Conclusions & Plans

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- MATHUSLA is a **complementary detector**
  - ✓ Might make the LHC LLP search program more comprehensive
  - ✓ Might have the potential to significantly **enhance and extend the new physics reach** and capabilities of the current LHC detectors
- Planning to build a **demonstrator**  $\sim (9\text{m})^2$  made up of a **few construction units**
  - ✓ Will **validate the design and construction procedure of individual units**. It will provide **reliable input to the cost and schedule for MATHUSLA**
- Goal to complete the Technical Design Report (TDR) by end 2020
- **Need expertise to develop the detector technology** and build the demonstrator/MATHUSLA
- **Several applications** for **resources** on-going in **Europe (>1 ERC proposals), USA and Canada**

- ❖ We are a small group → lots of possibilities/visibility for postdocs, PhD, grad students
- ❖ We might be able to start working on the demonstrator at the beginning of next year
- ❖ **Consider joining the Collaboration!**

❑ If interested: [Cristiano.Alpigiani@cern.ch](mailto:Cristiano.Alpigiani@cern.ch) , [mathusla.experiment@cern.ch](mailto:mathusla.experiment@cern.ch)

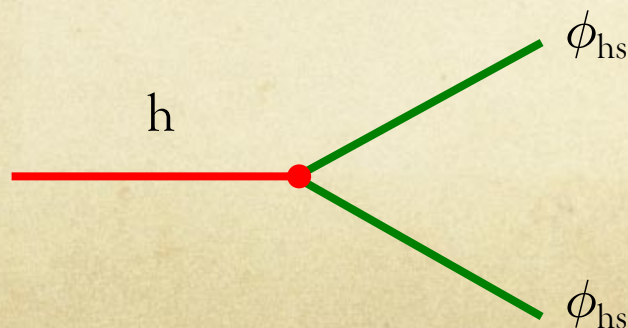


BACKUP

# The Hidden Sector

- The Standard Model (SM) is in amazing agreement with the experimental data, but **still some problems remain unsolved**: dark matter, neutrinos masses, hierarchy, matter-antimatter asymmetry...
- Many extensions of the SM (Hidden Valley, Stealth SUSY, 2HDM, baryogenesis models, etc) include particles that are **neutral, weakly coupled**, and **long-lived** that can decay to final states containing several hadronic jets
- Long-lived particles (LLPs) occur naturally in **coupling to a hidden sector (HS)** via small scalar (Higgs) or vector ( $\gamma$ , Z) portal couplings

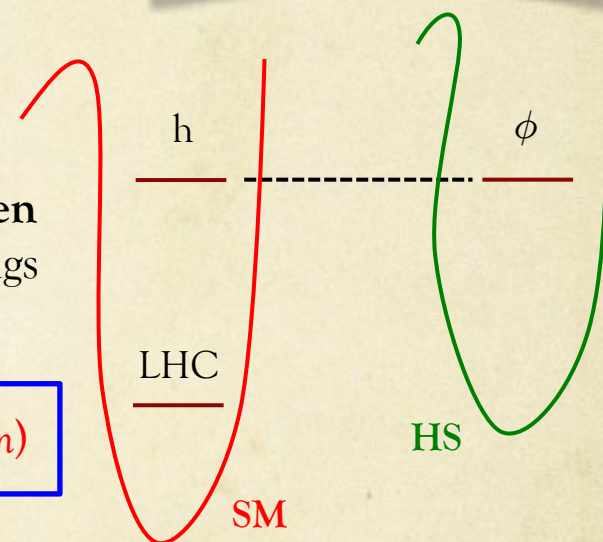
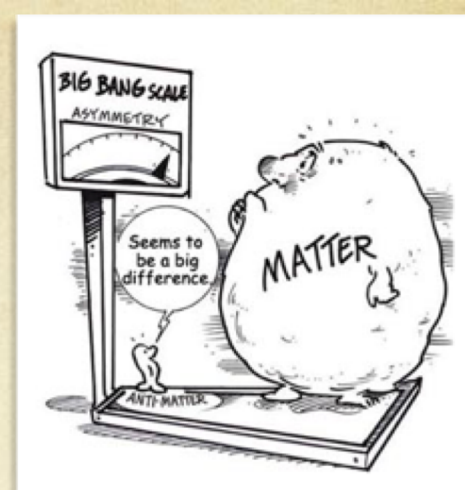
❖ Wide range of possible lifetimes from  $\mathcal{O}(mm)$  up to  $\mathcal{O}(m/km)$



The mixing of Higgs with HS results in a Higgs like particle decaying into LLPs:

**small coupling  $\rightarrow$  long lifetimes** [Phys. Lett. B6512 374-379, 2007]

**$\sim 10^8$  Higgs boson @ HL-LHC**





# Signature Space of Displaced Vertex Searches

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- Detector signature depends of production and decay operators of a given model
  - Production determines cross section and number and characteristics of associated objects
  - Decay operator coupling determines life time, which is effectively a free parameter
- Common Production modes
  - Production of single object - with No associated objects (AOs)
    - Higgs-like scalar  $\Phi$  that decays to a pair of long-lived scalars,  $ss$ , that each in turn decay to quark pairs – Hidden Valley, Neutral Naturalness, ...
    - Vector ( $\gamma_{\text{dark}}, Z'$ ) mixing with SM gauge bosons – kinetic mixing
  - Production of a single object P with an AO – Many SUSY models
    - AO jets if results from decay of a colored object
    - AO leptons if LLP produced via EW interactions with SM
- Common detector signatures  $\Rightarrow$  generic searches

# Neutral Long-lived Particles

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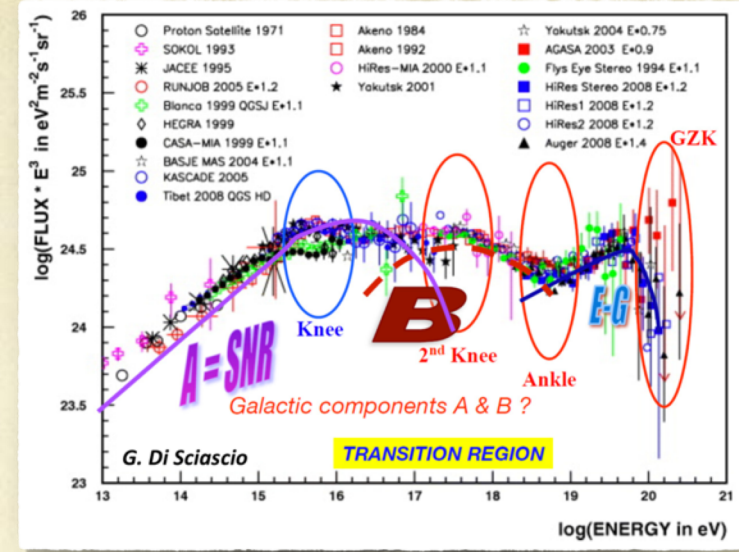
- Neutral LLPs lead to displaced decays with no track connecting to the IP, a distinguishing signature
  - SM particles predominantly yield prompt decays (good news)
  - SM cross sections very large (eg. QCD jets) (bad news)
- To reduce SM backgrounds many Run 1 ATLAS searches required two identified displaced vertices or one displaced vertex with an associated object
  - Resulted in good rejection of rare SM backgrounds
  - BUT limited the kinematic region and/or lifetime reach
- None the less, these Run 1 searches were able to probe a broad range of the LLP parameter space (LLP-mass, LLP- $c\tau$ )
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent



# MATHUSLA - Cosmic Rays - EAS

- KASCADE is currently a leading experiment in this energy range
  - ✓ Has larger area than MATHUSLA100 (40,000 m<sup>2</sup> vs 10,000 m<sup>2</sup>) but ~100 % detector coverage in MATHUSLA vs < 2 % in KASCADE
- MATHUSLA has better time, spatial and angular resolution, and five detector planes

## ❑ MATHUSLA standalone



- ✓ Measurements of arrival times, number of charged particles, their spatial distributions → allow for reconstruction of the core, the direction of the shower (zenith and azimuthal angles), slope of the radii distribution of particle densities, total number of charged particles (core shape is not well studied → MATHUSLA could provide new information)

## ❑ MATHUSLA+CMS/ATLAS

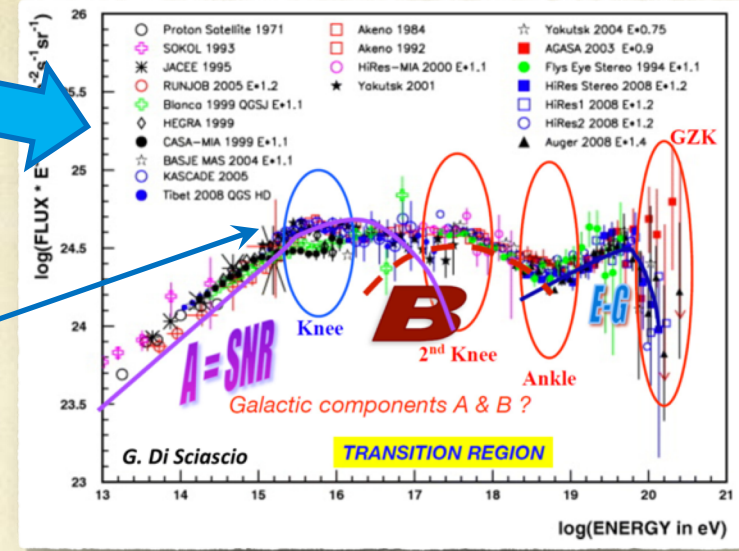
- ✓ Uniquely able to analyse muon bundles going through both detectors. This is a powerful probe of heavy primary cosmic ray spectra and astrophysical acceleration
- ✓ Lot of time to connect MATHUSLA with CMS/ATLAS bunch crossing (at HL-LHC trigger has ~12 microsecond latency)

Guaranteed return on the investment!

# MATHUSLA - Cosmic Rays – Energy Spectrum

## Several structures in the current measurements

- Good measurements in the energy range  $10^{15}$ - $10^{17}$  eV is crucial to understand the **transition** from **galactic** to **extragalactic** cosmic rays
- Understanding the **knee** may be the **main open problem in cosmic ray physics** (requires high statistic and good measurements to establish the components of source and distribution of incident particles)
- The full coverage of MATHUSLA100 will allow a **lower energy threshold** ( $\sim 100$  GeV) than KASCADE ( $\sim 1$  PeV)
  - ✓ Lower threshold allows **comparison with satellite measurements** (CREAM, Calet, HERD)
- With the ability to measure several different parameters it should be possible to **separate** with decent statistics **p+He**, **intermediate mass nuclei** and **Fe** up to  $10^{16}$  eV
- MATHUSLA **multiple tracking layers** may help to **understand the energy spectrum**
- Extending the linearity of analog measurements by a factor of 10 greater than ARGO-YBJ MATHUSLA may be able to **measure shower energies above a PeV** ( $\sim 10^{17}$  eV)



Guaranteed return on the investment!



**MATHUSLA detector** → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutral **p**Articles

- Dedicated detector **sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis** (BBN) limit ( $10^7 - 10^8$  m) for the HL-LHC
- **Large-volume, air filled detector located on the surface** above and somewhat displaced from ATLAS or CMS interaction points
- HL-LHC → **order of  $N_h = 1.5 \times 10^8$**  Higgs boson produced
- Observed decays:

$$N_{\text{obs}} \sim N_h \cdot \text{Br}(h \rightarrow \text{ULLP} \rightarrow \text{SM}) \cdot \epsilon_{\text{geometric}} \cdot \frac{L}{bc\tau}$$

$\epsilon$  = geometrical acceptance along ULLP

$L$  = size of the detector along ULLP direction

$b \sim m_h / (n \cdot m_X) \leq 3$  for Higgs boson decaying to  $n = 2$ ,  $m_X \geq 20$  GeV

- ❖ To collect a few ULLP decays with  $c\tau \sim 10^7$  m requires a 20 m detector along direction of travel of ULLP and about 10% geometrical acceptance

$$L \sim (20 \text{ m}) \left( \frac{b}{3} \right) \left( \frac{0.1}{\epsilon_{\text{geometric}}} \right) \frac{0.3}{\text{Br}(h \rightarrow \text{ULLP})}$$

# MATHUSLA – Muon Rates from LHC

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- Simulated muons coming from LHC and passing 100 m of rocks made of **45.3m of sandstone**, **18.25m of marl** (calcium and clay), **36.45m mix** (marl and quartz)
- Minimum energy  $\sim 70$  GeV
- What a muon can do inside the detector?
  - ✓ **Pass through**  $\rightarrow$  detected as a single upwards track
  - ✓ **Decay**  $\rightarrow$  entirely to  **$e\nu\nu$**  (single e deflected wrt muon direction), but also to  **$eee + \nu\nu$**  with  $\text{BR} \sim 3 \times 10^{-5}$  (looks like a genuine DV decay, but rejected through floor layer veto or main trigger muon trigger)
  - ✓ **Inelastic scattering**  $\rightarrow$  off the air or the support structure (rejected using floor layer veto)
- ❖ **Over the entire HL-LHC run expected  $\sim 10^6$  muons pass through MATHUSLA**, corresponding to  $\sim 0.1$  Hz
  - ❑ **3000 muons** decaying to  **$e\nu\nu$**  (electron deflected from original muon trajectory by angle  $\sim 1/\text{muon boost}$  ( $\sim 5\text{-}10$  degrees))
  - ❑ **0.1 muons** decaying to  **$eee + \nu\nu$**
  - ❑  **$< 1$  muon scattering off air**



# The past...

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## ➤ 2016

- MATHUSLA idea proposed for the first time

## ➤ 2017

- Started working on the test stand design and construction
- First (short data taking period in P1) then cosmic ray tests in 887

## ➤ 2018

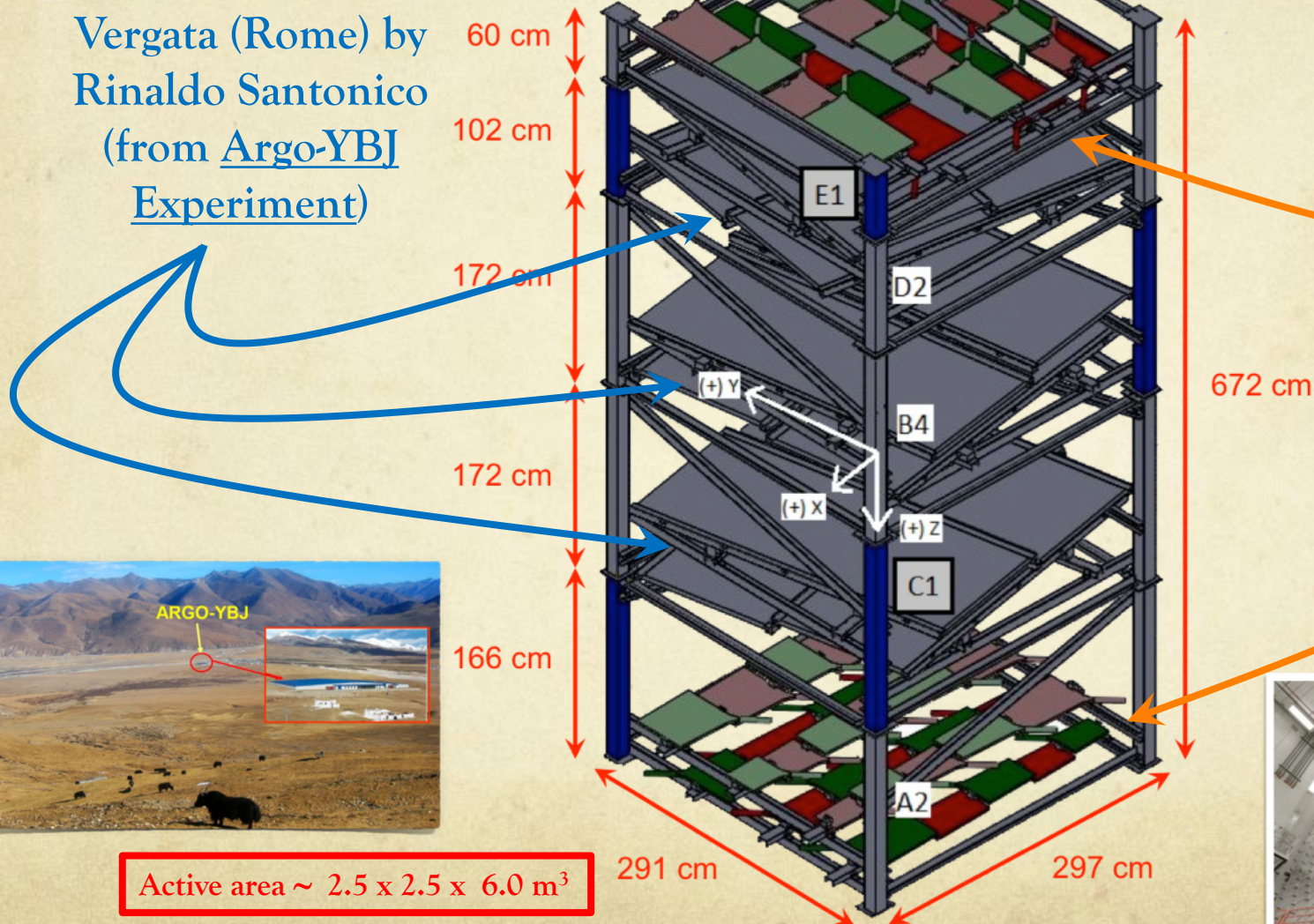
- P1 data taking
- Main detector design
- MATHUSLA White Paper
- MATHUSLA **LoI submitted to LHCC** (July 2018, [arXiv:1811.00927](https://arxiv.org/abs/1811.00927))

## ➤ 2019

- Cost estimate



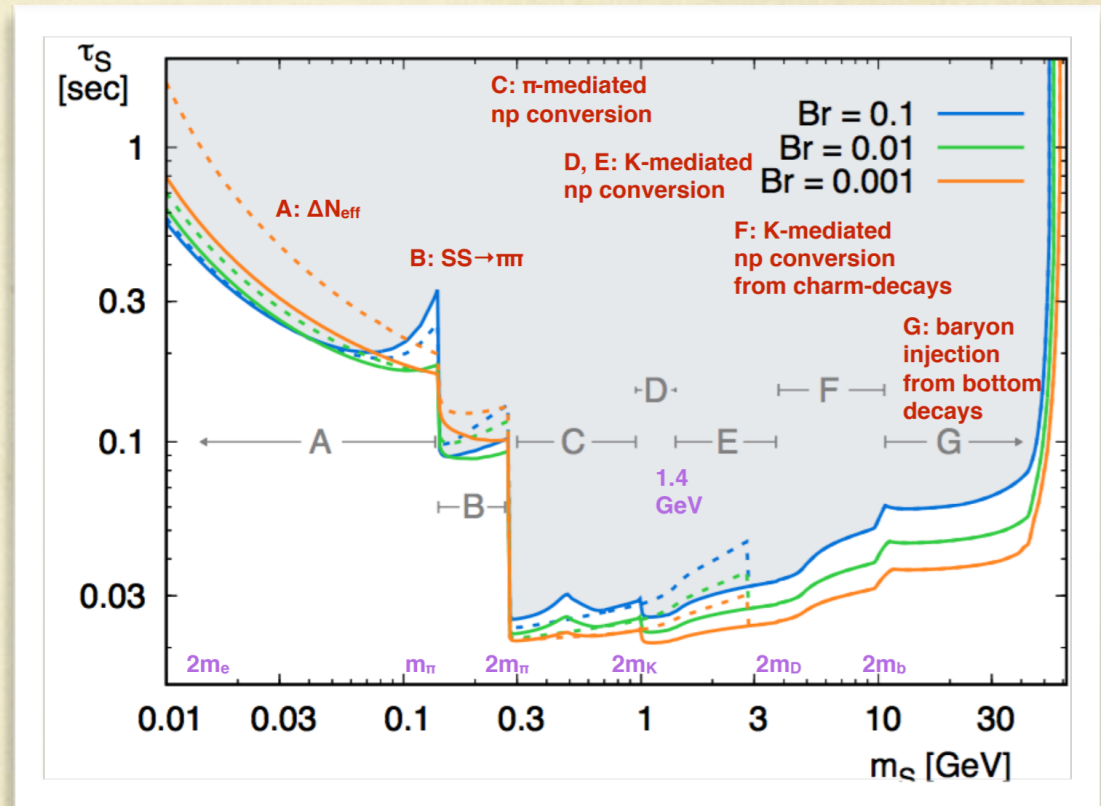
Top and bottom  
scintillator layers  
from Tevatron DØ  
provided by  
Dmitri Denisov





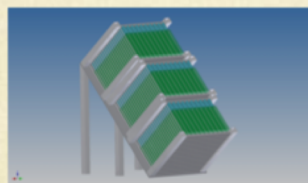
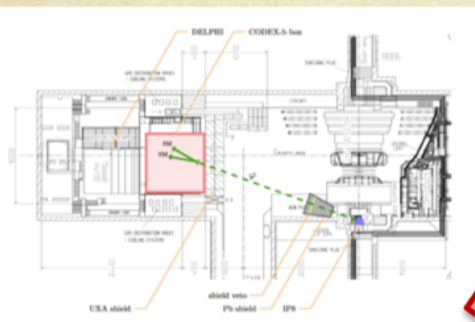
# MATHUSLA – Scalar LLP Lifetime Constraints

- A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via  $h \rightarrow ss$ , where the decay is induced by the small mixing angle of the Higgs field  $h$  and scalar  $s$ .
- For  $m_s > m_\pi$  the lifetime  $\tau < 0.1$  s.
- Conclusion does not depend strongly on  $\text{BR}(h \rightarrow ss)$

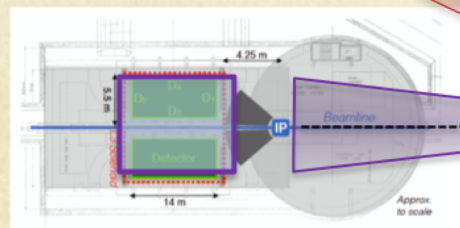


# New Projects @ LHC

## Codex-b



## MilliQan



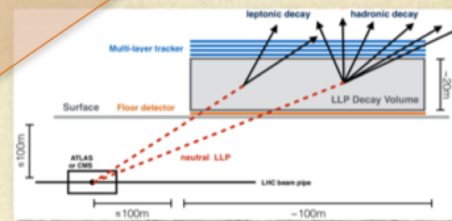
## AL3X

## ATLAS/CMS

~80 m

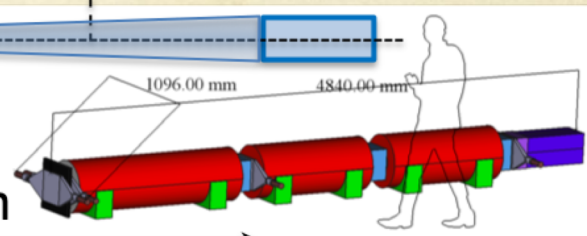
## MATHUSLA

~90 m



## FASER

~480 m



□ For long  $c\tau$  detector sensitivity  $\propto$  angular coverage and detector size

Experiment	$\eta$ coverage
MATHUSLA	0.9 - 1.4
AL3X	0.9 - 3.7
Codex-b	0.2 - 0.6

These experiments can exploit the full LHC potential and reduce to negligible the possibility of losing new physics at the LHC!